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OPERATIONALLY EFFICIENT PROPULSION SYSTEM STUDY (OEPSS) DATA BOOK

Volume III – Operations Technology

24 April 1990

Prepared for
Kennedy Space Center
NAS10-11568

Prepared by
John O. Vilja

Rocketdyne Study Managers: G. S. Wong/G. S. Waldrop
NASA, KSC Study Manager: R. E. Rhodes

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FOREWORD

This document is part of the final report for the Operationally Efficient Propulsion System Study (OEPSS) conducted by Rocketdyne Division, Rockwell International for the AFSSD/NASA ALS Program. The study was conducted under NASA contract NAS10–11568 and the NASA Study Manager is Mr. R. E. Rhodes. The period of study was from 24 April 1989 to 24 April 1990.

ABSTRACT

This study was initiated to identify operations problems and cost drivers for current propulsion systems and to identify technology and design approaches to increase the operational efficiency and reduce operations cost for future propulsion systems. To provide readily usable data for the ALS program, the results of the OEPSS study have been organized into a series of OEPSS Data Books as follows: Volume I, Generic Ground Operations Data; Volume II, Ground Operations Problems; Volume III, Operations Technology; and Volume IV, OEPSS Design Concepts. This volume identifies operations enhancing technology that responds to the operations concerns contained in Volume II. These technologies will greatly reduce the ground processing, support system, and facility requirements, and will simplify launch pad operations. A recommended technology development plan for each technology is presented.

ACKNOWLEDGMENT

The author wishes to express his sincere thanks to the following people for their efforts in assessing the propulsion technology needs, for future launch systems, described in this data book: Mr. R. D. Baily, Rocketdyne ALS Chief Project Engineer, and his project group for their critique; and many Rocketdyne Specialists in Engineering for contributing their technical expertise.

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1.0 INTRODUCTION

This data book describes the specific technology identified during the Operationally Efficient Propulsion System Study (OEPSS), which addresses the operations concerns identified during the study. The OEPSS study examined launch operations of all currently active American launch systems to determine which elements of the system have the greatest impact on operability in terms of cost, schedule, and reliability.

This launch site operations survey resulted in a list of 25 major operations concerns or problems that will require improvement in future launch system designs. This list is presented below and reflects the order of criticality as assessed by consensus of launch site personnel. Detailed descriptions of each of these operations concerns can be found in OEPSS Data Book Volume II, Ground Operations Problems.

1. Closed aft compartments
2. Hydraulic system (valve actuators and TVC)
3. Ocean recovery/refurbishment
4. Multiple propellants
5. Hypergolic propellants (safety)
6. Accessibility
7. Sophisticated heat shielding
8. Excessive components/subsystems
9. Lack hardware integration
10. Separate OMS/RCS
11. Pneumatic system (valve actuators)
12. Gimbal system
13. High maintenance turbopumps
14. Ordnance operations
15. Retractable T–O umbilical carrier plates
16. Pressurization system
17. Inert gas purge
18. Excessive interfaces
19. Helium spin start

20. Conditioning/geysering (LOX tank forward)
21. Preconditioning system
22. Expensive commodity usage – helium
23. Lack hardware commonality
24. Propellant contamination
25. Side–mounted booster vehicles (multiple stage propulsion systems)

The operations concerns that have been identified provided a basis for carefully examining the elements of the propulsion system that need to be addressed using existing technology and which will require additional technology development. It was found that many of the operations concerns can be addressed by existing technology, such as integrating and consolidating subsystems; however, further technology development is required to eliminate complex subsystems. An example of such technology would be the integration of the complex, multiple helium bottles and regulation systems into a single helium vessel with primary and backup regulation systems. This integration would simplify the launch system immensely; however, it would not address the capability to remove helium completely from the launch system altogether by designing–out the engine purge requirement.

The technology listed in this data book are those identified by the OEPSS team, which would begin removing operations–intensive subsystems from future launch vehicles. These significant operations enhancing technologies are listed below.

1. No–purge pump seals
2. No–purge combustion chamber (start–shutdown)
3. Oxidizer–rich turbine, LOX turbopump
4. Hermetically sealed inert engine (prelaunch)
5. Combined hydrogen systems (MPS, OMS, RCS, ECLSS, fuel cell)
6. Flash boiling tank pressurization
7. Low–NPSH pumps
8. Large flow range pumps
9. Differential throttling
10. Electric motor actuator (EMA)
11. No–leakage mechanical joints
12. Automated self–diagnostic condition monitoring system
13. Integrated propulsion module concept

14. Antigeyser, LOX tank aft propulsion concept
15. Rocket engine air–augmented afterburning concept

This data book describes for each technology (a) the operational objective, (b) the operations concerns specifically addressed, (c) a recommended development approach for new technology and those already under development, and (d) an approximate schedule for its development. Section 2.0 provides some examples of how technology could benefit launch operations.

2.0 OPERATIONS CONCERNS ADDRESSED BY TECHNOLOGY

The Operationally Efficient Propulsion System Study (OEPSS) examined launch operations of various vehicles to establish a listing of major ground operational concerns related to the propulsion system. These concerns were prioritized by interviewing launch site personnel, including representatives from the government, vehicle manufacturers, and Rocketdyne. In the OEPSS study, the propulsion system appropriately includes not only the engines but the entire system producing thrust and control. Thus, the propellant tankage, the complete fluid management system, thrust structure, and control system are considered as part of the total propulsion system in the study. This is the only way to avoid artificial interfaces. The OEPSS operations concerns list was then used to conceive a launch system that would achieve operational efficiency by addressing the operations concern and by either eliminating them or greatly mitigating them. This launch system, therefore, would have increased capability to achieve routine access into space without great risk or delays resulting from complex ground operations issues.

To illustrate how the operations concerns can be met by a hypothetical operationally efficient launch system and how technology can further enhance operational efficiency, a "strawman" vehicle concept will be used. First of all, the vehicle must eliminate the use of multiple propellants. All propulsion systems for the vehicle must use liquid oxygen and liquid hydrogen. These propulsion systems include boosters, core engines, orbital maneuvering engines, and attitude control thrusters. Propellant grade oxygen must also be used for fuel cells, thus eliminating an expensive and maintenance–intensive, high–grade oxygen system. These measures alone would eliminate many of the operations concerns by eliminating numerous propellant–handling systems and schedule delays caused by unique tanking requirements associated with using many different fuels.

2.1 COMMON LOX/LH_2 PROPELLANTS

There are many good reasons and advantages in using a common LOX/LH_2 propellant combination for all the vehicle fluid systems: they are readily available, relatively inexpensive, easily handled with existing procedures, environmentally acceptable, and they provide the highest level of performance of any commonly used propellant combination. They are the only known propellants that can be integrated not only for all propulsion power but can also be used for life support and thermal management. Their availability and storage procedures have become routine at major launch sites. Logistics are in place for their use, thus allowing easy transition to use for any future launch system.

Storable liquid propellants should not be used because of extensive handling issues, bulk availability, and environmental concerns associated with their use. They cannot be used for fuel cell power or life support nor are they suitable for thermal management. Existing launch operations dealing with storables have experienced many schedule delays since most operations require area evacuation because of their highly toxic nature. Also the issue of availability would have to be addressed in an aggressive space exploration program since current production rates would rapidly consume the nation's production of these chemicals. The final issue involves the ever–increasing environmental pressures over the shipping and use of these propellants. On-pad launch vehicle failures involving these propellants have caused evacuations in local communities downwind of the highly toxic cloud.

Similarly RP-1, or kerosene, should be eliminated because it poses concerns on the environment during fuel-lead starts and on-pad aborts. Though its problems are not as severe as those associated with hypergolic storables, they can cause severe impact on launch sites as a result of unburned fuel contamination. On-pad aborts can also pose a safety issue since, unlike hydrogen, RP-1 will form flammable pools, which could endanger personnel and hardware. Leakage into the ground water table is now a major issue in both storage and distribution systems. This fuel cannot be used for fuel cell power or life support nor is it suitable for thermal management. RP-1 propellants also cannot be used for a single stage or 1 1/2 stage vehicle to orbit.

Solid rockets should be eliminated because of their complex ground-handling procedures, inherent operational inflexibility, and concerns on toxic emissions. Solids require increased operational constraints during vehicle stack-up since they are stacked with propellants in place, unlike liquids which are loaded at the pad. Also an issue is the solid rockets' lack of adaptability in thrust output to suit the needs of each individual mission. Issues on solid rocket motor emissions have come under closer scrutiny because of public health concerns. A truly operationally efficient system should be usable from any launch site without concern for public safety in the surrounding areas. Again, the solid motor cannot be integrated with any other functions such as OMS, RCS, fuel cell power, life support, and thermal management.

The use of a single propellant combination requires some technology development since integration of systems has not been previously attempted on the scale suggested by the OEPSS study. Several of the technologies proposed in this data book address issues associated with combining propellant systems.

2.2 PNEUMATIC SYSTEM

To achieve an operationally efficient launch vehicle, pneumatic requirements must be eliminated at the launch pad. This requirement is imposed because of the numerous operations problems that have occurred at the launch site involving pneumatic systems and their operation in the vehicle and on the ground that are manpower intensive and time consuming. This requirement meant the elimination of purges, pneumatically controlled actuators, and gas spin-assisted engine starts. The technology required to eliminate these functions is not available and must be pursued. Several operations technologies in this area are presented in this data book.

2.3 PRESSURIZATION SYSTEM

Propellant tank pressurization systems requiring engine-supplied propellants ducted to the propellant tanks should be eliminated. This elimination is the result of a two-fold concern. The first concern is associated with tank pressurization, such as heat exchangers, control valves, and long tubing runs, which require significant amounts of maintenance and checkout. Leak checks of these systems are typically the most complex of the whole vehicle. Ground systems and umbilicals will also require large amounts of manpower for maintenance, and this is a critical function occurring near T–zero with critical launch commit criteria. Launch schedule impacts have been incurred because of anomalies in these systems. The second and more important reason for eliminating pneumatic systems is the safety aspect. The Space Shuttle oxidizer heat exchanger has been characterized to contain several potential Class–1 failure modes. Class–1 failure modes are those which could cause loss of crew and vehicle. Current technology does not provide a suitable alternative to existing propellant tank repressurization systems. Several key technology areas addressing these issues are presented in this data book.

2.4 EXCESSIVE ARTIFICIAL INTERFACES

Another operations concern that seriously affects operational efficiency is the multiplicity of components and corresponding large number of artificial interfaces in the propulsion system. This is an operations issue because the interfaces require extensive leak checks of components and between the components. The leak and functional testing of propulsion systems makes up a very large part of the processing and servicing ground operations. Large parts inventories and numerous procedures for parts replacement add to the extensive operations support requirement. In addition, reliability is reduced by the many intricate parts. An operationally efficient vehicle should reduce parts count and eliminate those tasks associated with handling and servicing the numerous components. This data book addresses several technologies required to achieve these goals.

2.5 FULLY–INTEGRATED BOOSTER PROPULSION SYSTEM

A system that integrates the entire propulsion system to reduce the number of parts required will increase system operability and increase system reliability. Fifty percent reductions in major hardware requirements, such as turbopumps, propellant inlet lines, and gas generators, are possible with this approach. Technology issues, such as transient simulation and structural review, are being studied. The integrated system addresses up to 16 of the 24 operations concerns by either reducing system complexity or eliminating systems altogether when combined with other technology.

A conceptual design of a fully–integrated booster propulsion system is illustrated in Figure 2–1. This figure shows some of the key features of a booster propulsion module as compared to an equivalent module of a cluster of single autonomous engines. This module reduces the turbopump count by manifolding a minimum number of turbopumps to feed the thrust chambers. Reliability is also enhanced by manifolding because if one turbopump shuts down, the remaining turbopumps could throttle up to maintain all thrust chambers at full operation. This concept is described in OEPSS Data Book: Volume IV – Design Concepts.

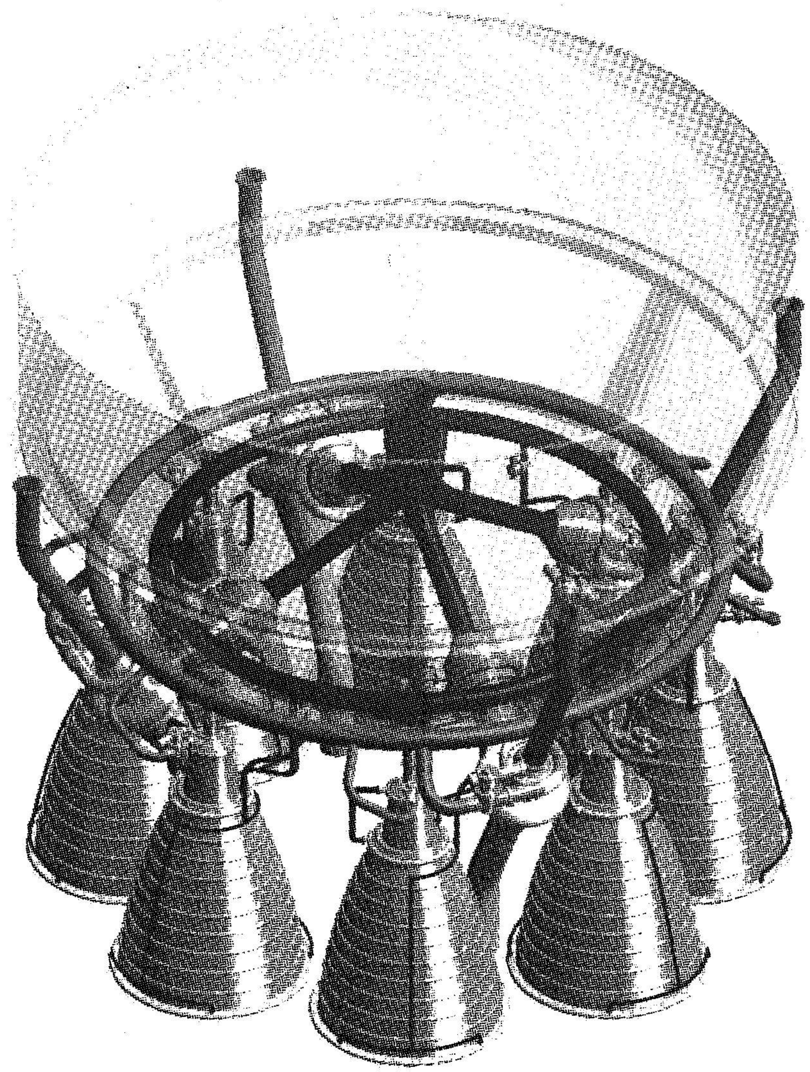
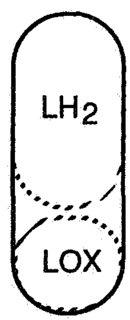


Figure 2–1. Fully Integrated Booster Propulsion System

2.6 LOX TANK-AFT PROPULSION SYSTEM

Another longer term technology is the antigeyser, LOX tank–aft propulsion system. In this system, the oxidizer tank is located at the aft end of the propellant tank stack. The greatest operational gain is with both the oxidizer and fuel tanks being located so that the turbopump feedlines are short. Other advantages are that the LOX turbopump can be located near the tank, thus, eliminating the conditioning required to start the engine, i.e., resulting in no Launch Commit Criteria (LCC) start box. Also, the LOX transfer and loading can be performed by pressure, thus, deleting the ground pump and resulting in a greatly simplified system. Pogo may also be eliminated. A greatly simplified chill procedure will potentially eliminate destructive geysering. Geysering is the phenomenon where gases from saturated propellant combine to form a Taylor bubble that empties the vertical feedline as it rises. This gas bubble can spray cryogenic liquid into the ullage gases, causing them to collapse resulting in tank negative pressure. When the liquid in the tank refills the feedline, it will collapse the gas and result in a severe water hammer effect felt throughout the system. This effect can cause severe damage resulting in the loss of the vehicle. The LOX tank–aft configuration eliminates this effect as the L/D of the feedline will not produce a destructive geyser. Disadvantages of this system include increased engine gimbal requirements and increased tankage weight. A LOX tank–aft configuration is illustrated in Figure 2–2. Other configurations that would reduce the LOX line lengths are multiple parallel tanks, concentric tanks, and toroidal tanks. These systems are described in OEPSS Data Book: Volume IV – Design Concepts.

- **Reverse tank positions (LOX aft, LH_2 fwd)**



- Short LOX feed lines greatly reduce pogo and eliminate geysering concern
- Smaller LOX tank results in shorter feed lines from forward tank
- Weight reduction of feed lines, LH_2 tank and intertank structure
- Large reduction in propellant conditioning required for LOX loading and engine start on LOX side
- Reduced control authority from aft C.G. location
- Cost similar to ALS vehicles

Figure 2–2. LOX Tank Aft Propulsion System

2.7 AIR-AUGMENTED AFTERBURNING SYSTEM

The longest term technology included in this data book is the combined cycle, ejector/rocket engine afterburning concept illustrated in Figure 2–3. This concept increases the operational efficiency of the overall propulsion system by reducing the number of major system components and ground support systems required because of the reduced oxidizer tankage requirement. This concept is particularly applicable to a single–stage vehicle if the oxidizer propellant requirement is reduced substantially to eliminate virtually duplicate systems, such as complete booster stages and their

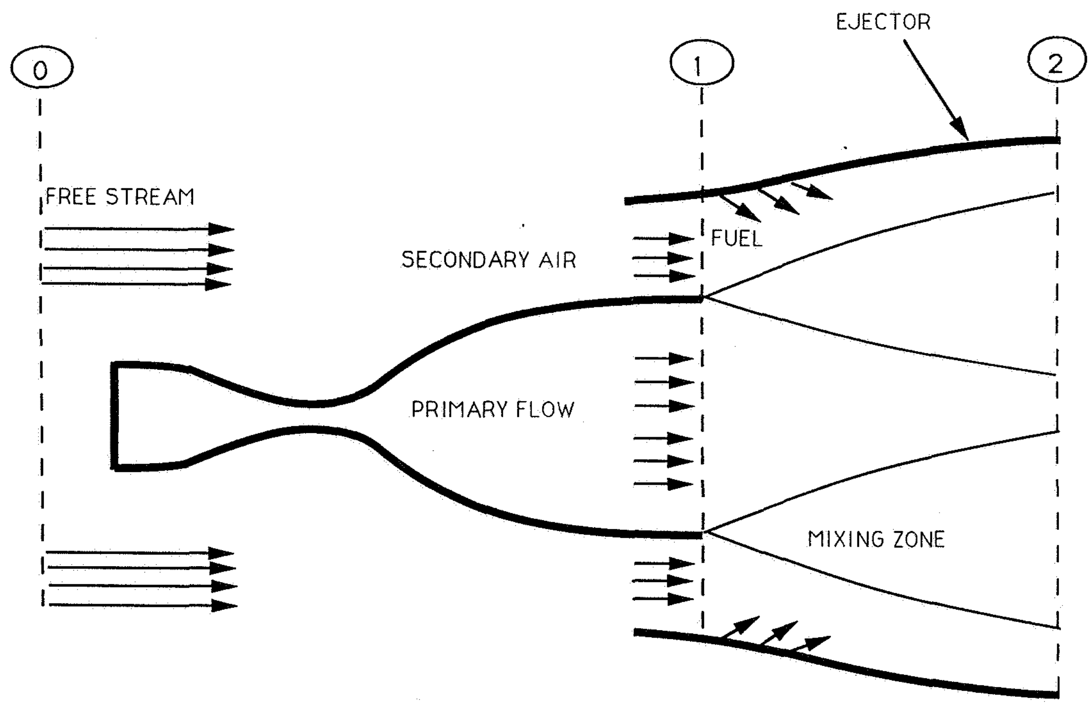


Figure 2–3. Rocket Engine Air Augmented Afterburning Concept

propulsion hardware. This concept is described in OEPSS Data Book: Volume IV – Design Concepts.

2.8 OPERATIONALLY EFFICIENT LAUNCH SYSTEM

An operationally efficient launch vehicle could be achieved by applying the following system technology:

- Eliminate multiple propellants and use a common set of LOX/LH_2 propellants for both main propulsion and auxiliary systems
- Eliminate pneumatic and pressurization systems
- Eliminate excessive autonomous subsystems by integrating subsystems to reduce the number of components
- Eliminate long LOX lines by using parallel tanks

Figure 2–4 depicts the operationally efficient launch vehicle that could be realized by applying the above technologies and identifies key areas of simplification. This system would greatly simplify the support infrastructure (facilities, equipment logistics, and manpower) required for processing the vehicle and reduce the associated operations cost substantially over that for a conventional vehicle. The processing of this vehicle would be reduced to simple checkouts of the engines requiring no hands–on functions as they arrived at the launch site, transportation to the launch pad, fueling of the vehicle, then launch. With the elimination of ground service and potential delays in vehicle processing, this system would be capable of providing routine access to space.

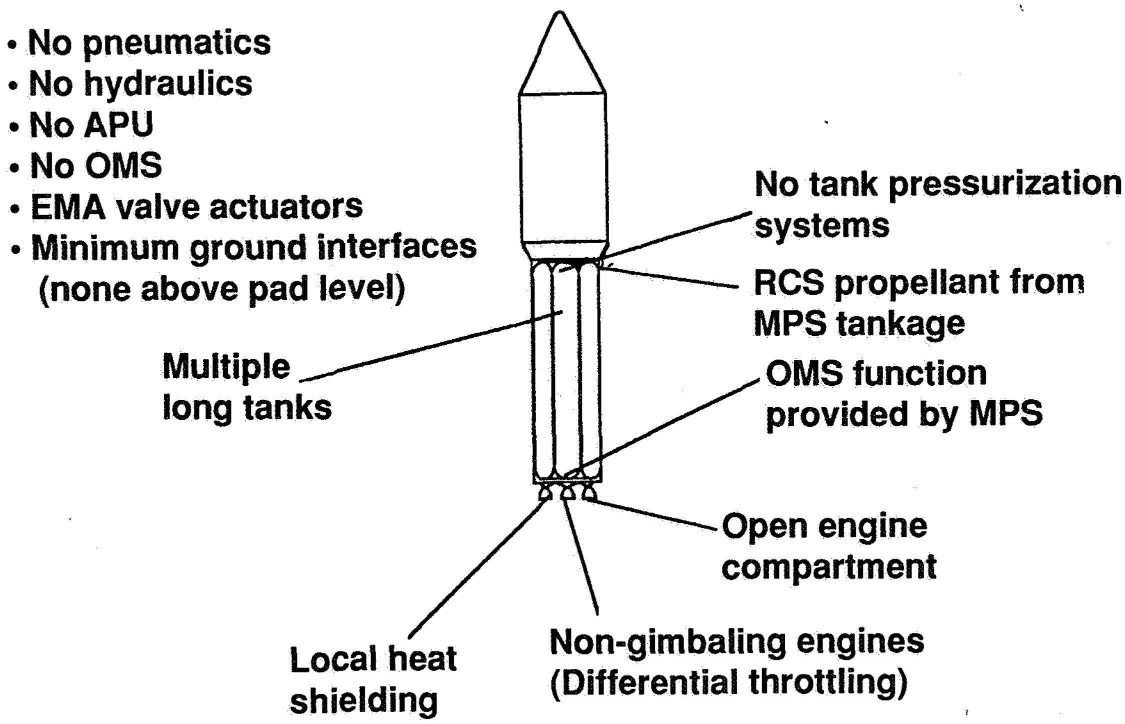


Figure 2–4. Operationally Efficient Launch System

3.0 OPERATIONS TECHNOLOGY

The technology items identified by the OEPSS study and listed in Section 1.0 must be pursued vigorously if a truly operationally efficient launch vehicle is to be achieved and if an order–of–magnitude reduction in operations cost is to be accomplished. The manner in which each technology addresses the many operations concerns listed in Section 1.0 is shown by the matrix in Figure 3–1. This matrix shows that the collective list of technology items addresses all the operations concerns in Section 1.0 with the exception of On–board ordnance (No. 14), which will continue to be required for range safety considerations, and Side–mounted vehicle (No. 25), which is a vehicle design issue. The three items at the end of the technology list in Section 1.0 are concepts that combine several technologies and are system concepts requiring further long–term study. In addition, the technologies listed are not limited to simultaneous application on a new launch system but would be applicable on an individual basis to existing and near–term vehicles as the technologies become mature.

Figure 3–2 shows the potential application of the technologies to existing and future launch vehicles. The application of these operations technologies would not only increase the operability of these systems but would also substantially reduce their life cycle cost once the technologies are available for implementation. Also, in some cases, they will increase vehicle performance and reliability. They will also allow them to be available to launch when needed. In Figure 3–2, the launch vehicle abbreviations, designated from left to right, are as follows:

STS	Space Transportation System (Space Shuttle)
Sh–C	Shuttle–C
LRB	Liquid Rocket Booster
ELV	Expendable Launch Vehicle (Delta, Atlas, and Titan)
ALS	Advanced Launch System
Sh–II	Shuttle–II

The first eight technology items in Section 1.0 are not currently under development and are, therefore, applicable to future launch systems. These will be discussed in Section 4.0 to 11.0. The remaining technology items on the list, i.e.,

(9) Differential throttling

(10) Electric motor actuator (EMA)

(11) No–leakage mechanical joints

(12) Automated, self–diagnostic, condition monitoring system

OEPSS Concerns: ~~1~~ ~~2~~ ~~3~~ ~~4~~ ~~5~~ ~~6~~ ~~7~~ ~~8~~ ~~9~~ ~~10~~ ~~11~~ ~~12~~ ~~13~~ 14 ~~15~~ ~~16~~ ~~17~~ ~~18~~ ~~19~~ ~~20~~ ~~21~~ ~~22~~ ~~23~~ ~~24~~ 25

Technology	OEPSS Concerns Addressed
• No purge pump seals	8 17 18 22
• No purge combustion chamber (start-shutdown)	8 17 18 21 22
• Oxidizer-rich turbine, LOX turbopump	8 13 17 22
• Hermetically sealed inert engine and tanks (prelaunch)	8 17 18 21 22 24
• Combined O_2/H_2, MPS, OMS, RCS, fuel cell, thermal control systems	4 5 8 9 10 24
• Flash boiling tank pressurization	8 9 16 18 24
• Low NPSH pumps	13 16 19 21
• Large flow range pumps	8 13 19 21
• Differential throttling	2 7 8 12
• Electric Motor Actuator (EMA)	2 6 9 11 12 15 18 24
• No leakage mechanical joints	1 2 3 5 8 11 16 17 18 21
• Automated, self-diagnostic, condition monitoring system	1 6 11 12 13 15 21 24
• Integrated modularized propulsion module concept	1 2 3 6 7 8 9 11 12 13 18 19 21 22 23 24
• Anti-geyser, LOX tank aft propulsion concept	9 19 20 21
• Rocket engine, air-augmented afterburning concept	3 9 16 17

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Figure 3–1. Operations Concerns Resolved by Technology

Technology	Vehicle Systems						
	STS	Sh-C	LRB	ELV	ALS	Sh-II	Space
• No purge pump seals		X	X		X	X	X
• No purge combustion chamber (start-shutdown)		X	X	X	X		X
• Oxidizer-rich turbine, LOX turbopump		X	X	X	X	X	X
• Hermetically sealed inert engine and tanks (prelaunch)			X	X	X		
• Combined O_2/H_2 MPS, OMS, RCS, fuel cell, thermal control systems		X			X	X	X
• Flash boiling tank pressurization			X	X	X	X	X
• Zero - NPSH pumps			X	X	X	X	X
• Large flow range pumps			X	X	X	X	X
• Differential throttling				X	X	X	
• Electric Motor Actuator (EMA)	X	X	X	X	X	X	X
• No leakage mechanical joints		X	X	X	X	X	X
• Automated self-diagnostic condition monitoring system	X	X	X	X	X	X	X
• Integrated modularized propulsion module concept		X	X	X	X	X	X
• Anti-geyser, LOX tank aft propulsion concept			X	X	X	X	
• Rocket engine, air augmented afterburning concept			X		X	X	

Figure 3–2. Operations Technology Application

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are currently in various stages of development in ongoing programs or are combinations of technology, rather than a discrete technology, such as a system for differential throttling. These items are briefly discussed below.

3.1 DIFFERENTIAL THROTTLING

Differential throttling is an area that does not lend itself to technology development as such since any usage of this technique would be highly vehicle configuration specific. This concept is applicable to an engine cluster of at least three or more engines arranged in more than a single gimbal plane. Instead of pivoting engine thrust chambers to control the vehicle thrust vector, engines are throttled independently. The operational advantages of this system are that it eliminates the need for gimbal actuators, sophisticated articulating heat shields, flexible propellant ducts, as well as numerous other high–maintenance parts. The disadvantages of this system are a major reduction in control authority and the requirement for significant engine throttle range. Both issues are mitigated as the number of engines on a vehicle are increased. This concept is particularly applicable to a fully integrated propulsion system. An alternate to differential throttling would be to use jet air vanes that come closer to matching the control authority of gimballing.

3.2 ELECTRIC MOTOR ACTUATORS (EMA)

The EMAs are electromechanical devices used for engine valve positioning or gimbal actuation. Both areas are under development in support of the Advanced Launch System (ALS) program. Advantages of this system are the elimination of hydraulic and pneumatic requirements, increased hardware accessibility, reduced interfaces, simplified hardware checkouts, and reduced fluid contamination concerns. It also results in overall weight savings. Development of this type of actuator has been postponed since previously designed engine systems have depended on hydraulic and pneumatic availability to the engines in their initial ground rules. The hydraulic system would be hard to protect against the thermal environment and would require a closed aft compartment.

3.3 NO–LEAKAGE MECHANICAL JOINTS

No–leakage mechanical joints are also under development for the ALS program. Heavyweight versions of these systems have been in use for years in nuclear power plants. They use a welded seal rather than the conventional bolted flange, with a pressure actuated seal, currently used in rocket engine design. This item addresses 10 of the 25 operations concerns identified by the OEPSS study. In each of these cases, the item does not solve the issue but does significantly reduce the concern caused by each issue.

3.4 AUTOMATED, SELF–DIAGNOSTIC, CONDITION MONITORING SYSTEM

Automated, self–diagnostic, condition monitoring systems for rocket engines have been in work for several years on both the SSME and ALS programs. These systems monitor the engine system during operation to provide information on hardware condition during and following operation. The goal of these studies is to produce a system that will not only provide safe, reliable isolation and correction of a failed component in system operation and avoid engine shutdown in the event of a component failure, but will also provide maintenance data that reflect reduced postflight engine servicing requirements. Such systems would address eight operational concerns by reducing the work required to maintain engine systems. Launch processing times would be greatly reduced by these systems on any vehicle in which they were incorporated.

3.5 OTHER TECHNOLOGIES

In the following sections, the technology development required for the first eight technology items will be described. These include:

(1) No–purge pump seals

(2) No–purge combustion chamber

(3) Oxidizer rich turbine, LOX turbopump

(4) Hermetically sealed inert engine

(5) Combined hydrogen systems

(6) Flash boiling tank pressurization system

(7) Low–NPSH pumps

(8) Large flow range pumps

The technology descriptions highlight major areas requiring further study and provide a rough order of magnitude of the time frame in which the technologies could be developed. Also described are: (a) how each technology addresses operations concerns, (b) a recommended development plan, and (c) an approximate development schedule. Table 3–1 was used for a reference to estimate the current maturity level of technology.

Table 3-1. Technology Maturity Levels

Level		
1	Basic principles observed and reported	
2	Conceptual design formulated	
3	Conceptual design tested analytically or experimentally	
4	Critical function breadboard demonstration	Advanced Development (levels 4–6)
5	Component or brassboard model tested in relevant environment	
6	Prototype or engineering model tested in relevant environment	
7	Engineering model tested in space	
8	Baselined into production design, flight qualified	
9	Flight proven	

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4.0 NO–PURGE PUMP SEALS TECHNOLOGY

The operational efficiency of the propulsion system would increase significantly if pneumatic requirements could be eliminated. This would reduce system cost, weight, and maintenance requirements while increasing reliability. Traditional engine systems have been designed to use pneumatics since oxidizer turbopumps require a helium buffer purge to separate the leakage of fuel rich turbine gases from the oxidizer being pumped. Once this turbopump seal purge requirement is in place, it becomes normal practice to utilize the pneumatic systems wherever they are most suited.

4.1 OPERATIONS CONCERNS ADDRESSED[1]

The elimination of a turbopump seal purge addresses 4 of the 25 operations concerns identified (Concerns No. 8, 17, 18, and 22). Concern No. 8 is addressed by allowing a reduction in system parts count, thus reducing the number of interfaces. Concern No. 17 is directly addressed since this would eliminate the largest inert gas purging requirement of the engine. Concern No. 18 would be mitigated by reducing vehicle interfaces and possibly removing helium usage for the entire propulsion system. Finally, Concern No. 22 is directly addressed by greatly reducing helium usage. The ability to eliminate the mandatory turbopump seal purge is the single greatest step in eliminating helium usage on rocket engines.

Two techniques for eliminating the turbopump seal purge merit further examination: the development of sealing systems which require no purge; and the development of oxidizer–rich turbine drive systems. A discussion of the oxidizer–rich drive is presented in Section 6.0.

4.2 TECHNOLOGY PROGRAM

The approach to the development of a no–purge seal package would be to address the issue in phases. The initial phase of investigation would be to determine what the actual LOX/turbine gas flammability limits are for the applicable pressure in the seal cavity where the two fluids meet. This will provide a quantifiable allowable leakage into the mixed drain cavity and then investigate seal configurations and arrangements that will reduce the leakage rates of the gases to below the flammability limit. Configurations providing natural separation of the leakage gases will be an important factor in the seal designs.

The next phase, initiated simultaneously with the flammability limits testing, would be to procure candidate seals and perform seal characterization testing in a turbopump simulated environment. Data do not currently exist to characterize most types of seals for operation in turbopump environments. This testing would also be applicable to future turbopump designs for any engine configuration.

The final phase in this technology development task would be to assemble a seal package, based on the results of the seal characterization testing, and perform testing to determine whether

[1]Reference: OEPSS Data Book: Volume II — Ground Operations Problems

adequate conditions exist in the mixed drain cavity to avoid flammability and the need for an inert purge. The seal package testing would provide the validation required to allow this technology to be incorporated into subsequent turbopump designs. Further issues, such as packaging and rotordynamic characteristics, would be addressed in turbopump specific cases as the technology is applied.

This technology task will require approximately 4 years, and the overall schedule is shown in Figure 4–1. The maturity of this technology is estimated to be Level 2 (see Table 3–1).

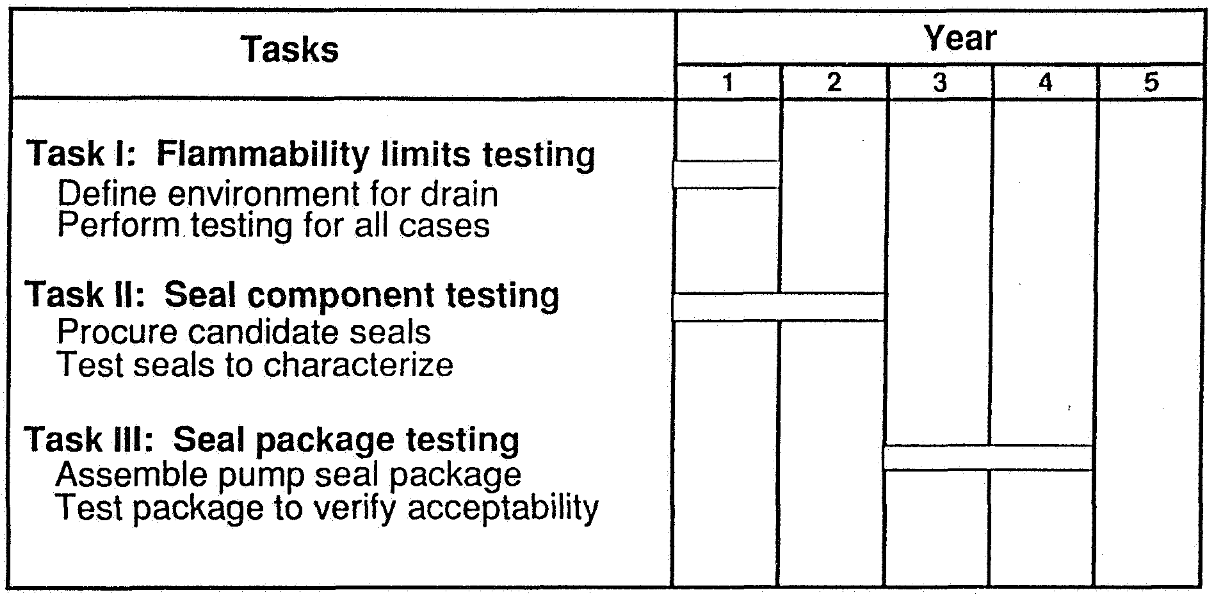

Figure 4–1. No–Purge Pump Seals Technology Program

5.0 NO-PURGE COMBUSTION CHAMBER TECHNOLOGY

The second most critical usage of pneumatic purge in a propulsion system, after the oxidizer turbopump intermediate seal purge, is the purge required by the engine prior to engine start and after engine shutdown. Current design practice utilizes prestart purges in the engine to provide an inert helium environment when cryogenic propellants are introduced downstream of the main propellant valves. Purges on the fuel side remove air which becomes potentially damaging ice when liquid hydrogen is introduced. Purges on the oxidizer side eliminate hydrogen blow–back into manifolds prior to introduction of liquid oxygen. Shutdown purges are used to blow out residual liquid oxygen from injector manifolds to preclude any slow burning that could result in injector damage.

5.1 OPERATIONS CONCERNS ADDRESSED

This technology addresses 5 of the 25 operations concerns (Concerns No. 8, 17, 18, 21, and 22). Since this technology would be a key in the removal of pneumatic systems from the engine, it addresses Concern No. 8 by allowing the removal of numerous components associated with purge pneumatics such as control valves, lines, filters, and check valves. Concern No. 17 is addressed directly by reducing inert gas purging requirements. Concern No. 18 is addressed since interfaces are reduced with the removal of pneumatic systems. Concern No. 21 is addressed by the simplification in engine preconditioning when purge sequences are eliminated. Concern No. 22 is addressed by eliminating the single greatest usage of helium, prestart purges. This technology along with several others would allow the removal of pneumatic systems from the launch vehicle main propulsion system.

5.2 TECHNOLOGY PROGRAM

The approach recommended for this technology task would be to perform a digital transient model start evaluation of a no–purge start sequence to determine how the start sequence could be modified to minimize solid air formation and hydrogen blowback. The modeling would be followed by analysis to determine what hardware issues are present.

Start modeling would be followed by shutdown modeling to determine sequences which would reduce residual liquid oxidizer levels. These analyses will be critical in determining precisely what component issues are involved and allow a focused effort in hardware redesign.

Once operational issues involved with no–purge engine operation are modeled, it will be possible to initiate preliminary design efforts to determine design approaches that will allow the desired simplified operation to be achieved. Low propellant volume injector manifolds and close–coupled, oxidizer valve configurations are seen as a key in eliminating the volume of unburned liquid oxygen following shutdown. Little work has been performed in this area since this is not a significant issue in engines with available pneumatic purges.

Another possible solution to purges is the use of fuel tank ullage gases to blow out any air downstream of the main fuel valve just prior to engine start. This would eliminate the icing issue, however, it would have to be evaluated for timing restrictions prior to engine start to preclude the formation of a large combustible hydrogen cloud outside the engine. This is not considered a major obstacle since it will be a matter of valve sequencing to remedy the situation.

These design concepts would then be applied to specific engine designs. No subscale test effort is included in the technology program since actual use will be highly engine geometry specific. Analysis work in the program would be performed on a well characterized engine system to achieve confidence in the results.

This initial technology task will require approximately 2 years of effort, and the overall schedule for the task is presented in Figure 5–1. The maturity of this technology is estimated to be Level 2.

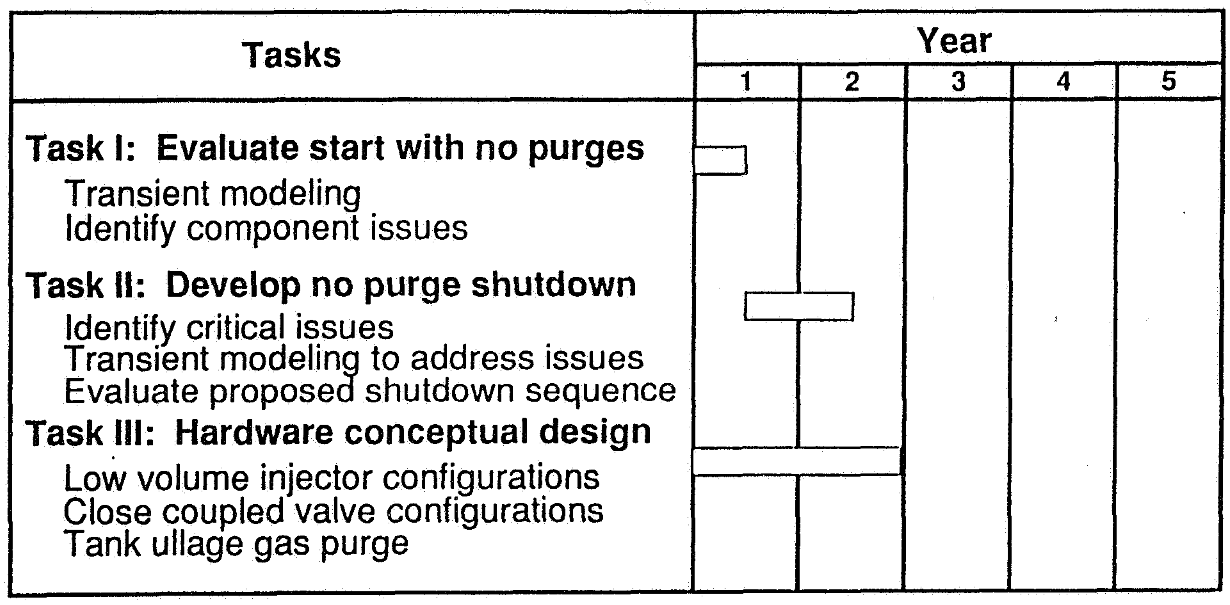

Figure 5–1. No–Purge Combustion Chamber Technology Program

6.0 OXIDIZER–RICH TURBINE TECHNOLOGY

One of the key features of an operationally efficient propulsion system is the elimination of pneumatic requirements. This would reduce system cost, weight, and maintenance requirements while increasing reliability. Current engine design practice uses pneumatics for numerous engine functions since oxidizer turbopumps require a helium buffer purge to separate fuel–rich turbine gases from the oxidizer being pumped.

6.1 OPERATIONS CONCERNS ADDRESSED

The elimination of a turbopump seal purge addresses 4 of the 25 operations concerns identified (Concerns No. 8, 17, 18, and 22). Concern No. 8 is addressed by allowing a reduction in system parts count, thus reducing the number of interfaces. Concern No. 17 is directly addressed since this would eliminate the largest inert gas purging requirement of the engine. Concern No. 18 would be mitigated by reducing vehicle interfaces and possibly removing helium usage for the entire propulsion system. Finally, Concern No. 22 is directly addressed by greatly reducing helium usage. The ability to eliminate the mandatory turbopump seal purge is the most significant step in eliminating helium usage on rocket engine systems.

One method for eliminating purges was discussed in the section on no–purge pump seals. Another method to eliminate oxidizer turbopump seal purges is to use oxidizer–rich turbine drive gas for the oxidizer turbopump. This technique eliminates the buffer purge since mixing of pump and turbine fluids would no longer be catastrophic. This system is purportedly in use by the Soviets in their Energia, Saturn V class launch vehicle.

This system has not been used widely for several reasons. First, it does not lend itself to an expander type application. Oxygen does not have the outstanding heat capacity characteristics of hydrogen and therefore is not as suitable for cooling the nozzle or combustion chamber to gain heat prior to expansion in the oxidizer turbopump turbine. Second, the issue of oxidizer coolant leakage into an otherwise fuel rich engine presents a safety issue which has not been adequately addressed. Finally, the use of an oxidizer rich preburning system has not been given adequate study to determine what hazards would be present and what could be done to eliminate them through design. This technology has never been given serious consideration in engine design because the basic development work has not been accomplished.

6.2 TECHNOLOGY PROGRAM

This technology task would address the issues associated with early development of such a system. The approach to development would center about a specific engine design to allow focused technology to emerge. The first step would be to analyze candidate engine cycles and configurations to determine which would be used for the focused technology work.

Concurrent with engine cycle analysis, oxygen compatibility characteristics would be reviewed to identify materials that could be used in an oxidizer–rich turbine design. Once the material property needs are identified, testing would be performed to obtain the necessary data to permit preliminary design work to be conducted on the selected engine configuration.

Another area which requires development is in oxidizer–rich injectors. Since oxygen is not very suitable for an expander system, such an injector would have a place in either a preburner or gas generator engine. This work would be done on a subscale level to identify any technical issues prior to incorporation in an actual engine design. Design and analysis would be performed to establish candidate configurations. Models would be constructed to allow air and water tests to establish flow characteristics. This would be followed by hot–fire demonstration on a subscale component. This would provide adequate data to consider incorporation of such injectors in future engine designs.

The final portion of this technology task would be to perform transient analysis on a selected engine configuration. Issues exist on how to start and shut down such a system since the standard practice of leading with fuel on all injectors may not be feasible and since turbine components cannot survive prolonged exposure to stoichiometric conditions. A digital transient model would be used to develop acceptable start and shutdown sequences. This would be followed by system analysis to identify critical areas within the engine during these operating phases. This task would address the major issues known today for such a system and is intended to provide adequate data to engine designers to study an oxidizer–rich turbine for future propulsion systems.

This technology task will require approximately 4 years, and the overall schedule for this task is shown in Figure 6–1. Portions could be selected for smaller study tasks. The maturity of this technology is estimated to be Level 3.

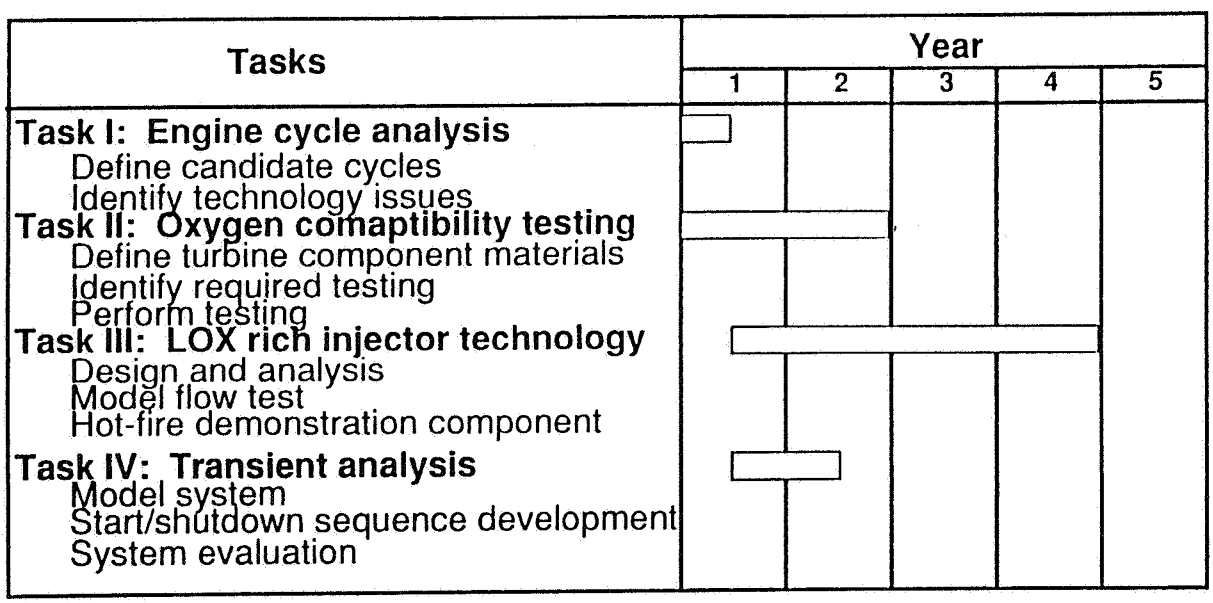

Figure 6–1. Oxidizer–Rich Turbine Technology Program

7.0 HERMETICALLY SEALED INERT ENGINE TECHNOLOGY

The desire to eliminate pneumatics from propulsion systems has now been well discussed. Prestart purges were cited as one of the areas requiring technology development if they are to be eliminated. Hermetically sealed inert engines would be a fall–back position should prestart conditioning purges remain a requirement for all start sequences and hardware configurations.

7.1 OPERATIONS CONCERNS ADDRESSED

The hermetically sealed inert engine concept addresses six operations concerns (Concerns No. 8, 17, 18, 21, 22, and 24). It addresses the five operations concerns addressed by the no–purge combustion chamber technology program as well as addressing Concern No. 24. The operations problem is over possible contamination in engine components. The sealed engine concept minimizes the possibility of externally supplied contamination by removing the possibility of externally introduced contamination into the injector.

The concept of the sealed engine is to deliver the installed engine to the launch pad filled with an inert gas, probably helium, between the main propellant valves and the throat or nozzle exit. This gas pocket would not require maintenance after departing the vehicle assembly building, and, therefore, will not require a pneumatic system in the launch vehicle.

7.2 TECHNOLOGY PROGRAM

The area requiring technology development for this concept is in the sealing of the inert gas in the engine. The approach recommended for the development of this concept is to define several sealing concepts which could provide the desired gas pocket which could be expelled without hindering operation of the engine after start. These seal concepts would be tested in full scale hardware simulators to determine their ability in sealing and expulsion.

The final phase would be to evaluate what operational impact the sealed engine system would have on launch operations. Issues requiring study include procedural changes, impact on engine checkouts, and effects on processing schedules if the seal is broken.

This initial technology task will require approximately 1 year depending upon the availability of various sealing concepts, and the overall schedule is shown in Figure 7–1. The maturity of this technology is estimated to be Level 3.

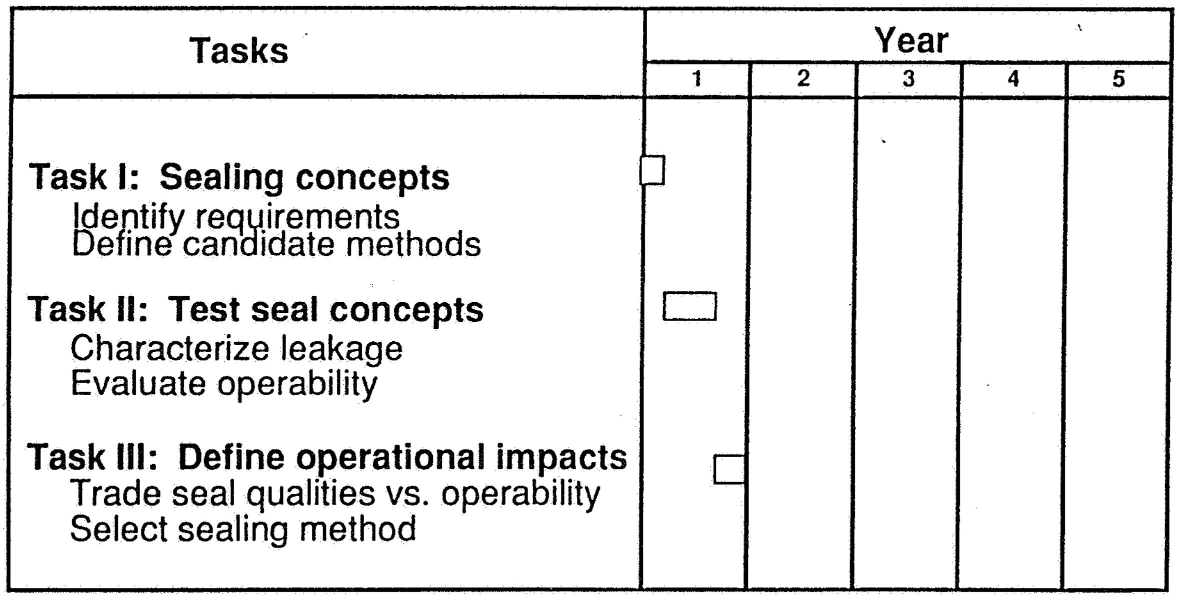

Figure 7–1. Hermetically Sealed Inert Engine Technology Program

8.0 COMBINED HYDROGEN SYSTEMS TECHNOLOGY (MPS, OMS, RCS, FUEL CELL, THERMAL MANAGEMENT)

One critical area of operational efficiency is in the reduction of the number of different commodities. The National Space Transportation System utilizes 6 separate propellants: propellant grade liquid hydrogen and liquid oxygen, hydrazine (N_2H_4), monomethyl hydrazine (MMH), nitrogen tetroxide (N_2O_4), and fuel cell grade liquid oxygen. These propellants all require extensive support systems and large numbers of specially trained personnel for acquisition, storage, and handling. Other fluid systems requiring extensive ground support systems and personnel are thermal management (presently accomplished with Freon–21, FC–40, water, and ammonia) and life support (chemical). If a launch vehicle could combine all its fluid systems to use a single oxygen/hydrogen propellant combination, a dramatic increase in operational efficiency would be achieved.

8.1 OPERATIONS CONCERNS ADDRESSED

This area of study directly addresses 6 operations concerns (Concerns No. 4, 5, 8, 9, 10, and 24). Concern No . 4 is addressed directly as it reduces the number of propellants to the minimum practical limit. Concern No. 5 is eliminated since hypergolic propellants are removed from the vehicle thus eliminating safety issues. Concerns No. 8 and 9 are addressed by reducing components by integrating hardware. Concern No. 10 is eliminated since, by definition, this task combines Orbital Maneuvering System and Reaction Control System functions. Concern No. 24 is addressed by eliminating the extremely contamination sensitive fuel cell grade oxygen. The value of this system can be seen by simply noting the high priority of the concerns addressed, i.e., half of the top 10 operations concerns are addressed.

Work has been performed on combining propulsion systems into an integrated oxygen/hydrogen system capable of providing main propulsion, orbital maneuvering, and reaction control functions. The most recent work was performed by Rockwell Space Transportation System Division for the NASA Lewis Research Center under the title Integrated Hydrogen/Oxygen Technology (IHOT) Program. This preliminary work has been valuable, but requires an increase in scope to include electricity producing fuel cells and vehicle thermal management.

8.2 TECHNOLOGY PROGRAM

The proposed approach would be to add to the IHOT study by expanding the scope of the investigation to include fuel cells and thermal management. Candidate systems would be evaluated for feasibility, cost, operability, technology, and potential applications. Options which best meet the criteria would be subject to more detailed study. Preliminary designs would be made to provide specific near term applications and subsystem/component technology items would be identified for development. This process would continue through prototype demonstration.

Since this area is not merely technology development but a true systems integration task, the value of prototype testing cannot be underestimated. Analytical modeling will be a valuable tool in the development of such systems; however, it is unlikely future vehicle designers will incorporate this technology until it is demonstrated at some physical level. The synergistic nature of such a combined system poses considerable early development challenge which is not usually considered in most success oriented hardware programs.

This technology task will require approximately 4 years, and the overall program schedule is shown in Figure 8–1. Although prototype system development is shown to be accomplished in 4 years, test bed testing with the main propulsion system (MPS) demonstrating full development verification should subsequently also be accomplished. This should be followed by a flight test demonstration with the Space Shuttle in an evaluation mode only. The maturity of this technology is estimated to be Level 3.

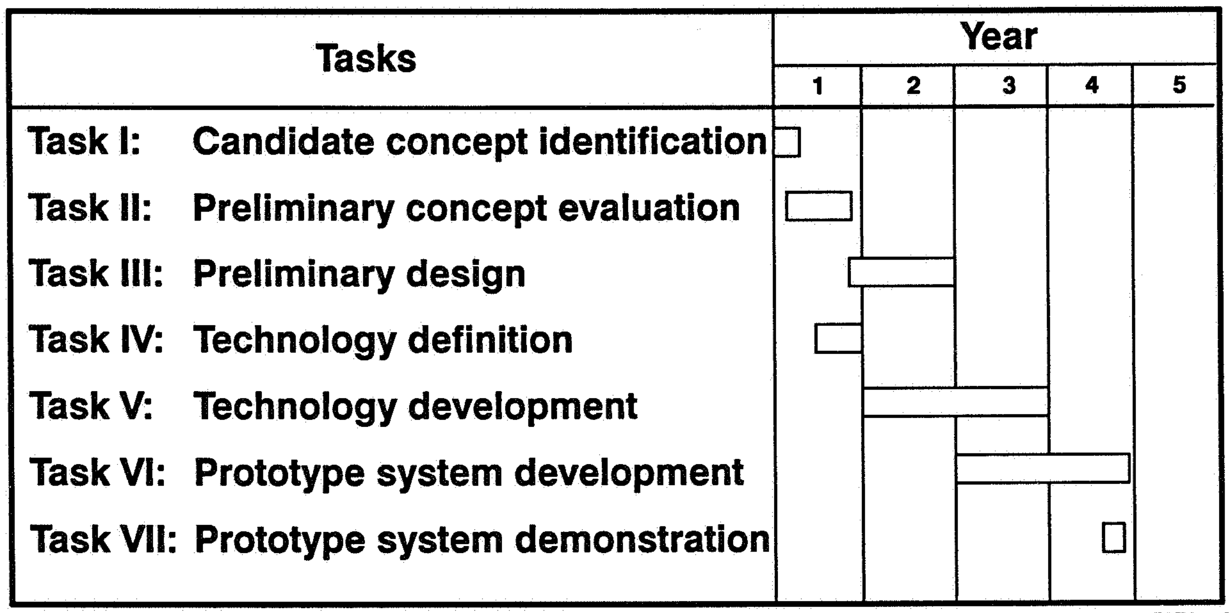

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Figure 8–1. Combined Hydrogen Systems Technology Program

9.0 FLASH BOILING TANK PRESSURIZATION TECHNOLOGY

To achieve an operationally efficient propulsion system, the use of engine supplied propellant tank pressurization flow should be eliminated because of the high maintenance required to assure the system is functioning correctly. Failure of this system can result in a catastrophic failure of the vehicle. An operationally efficient system must have a simplified pressurization scheme which minimizes or eliminates safety critical hardware.

9.1 OPERATIONS CONCERNS ADDRESSED

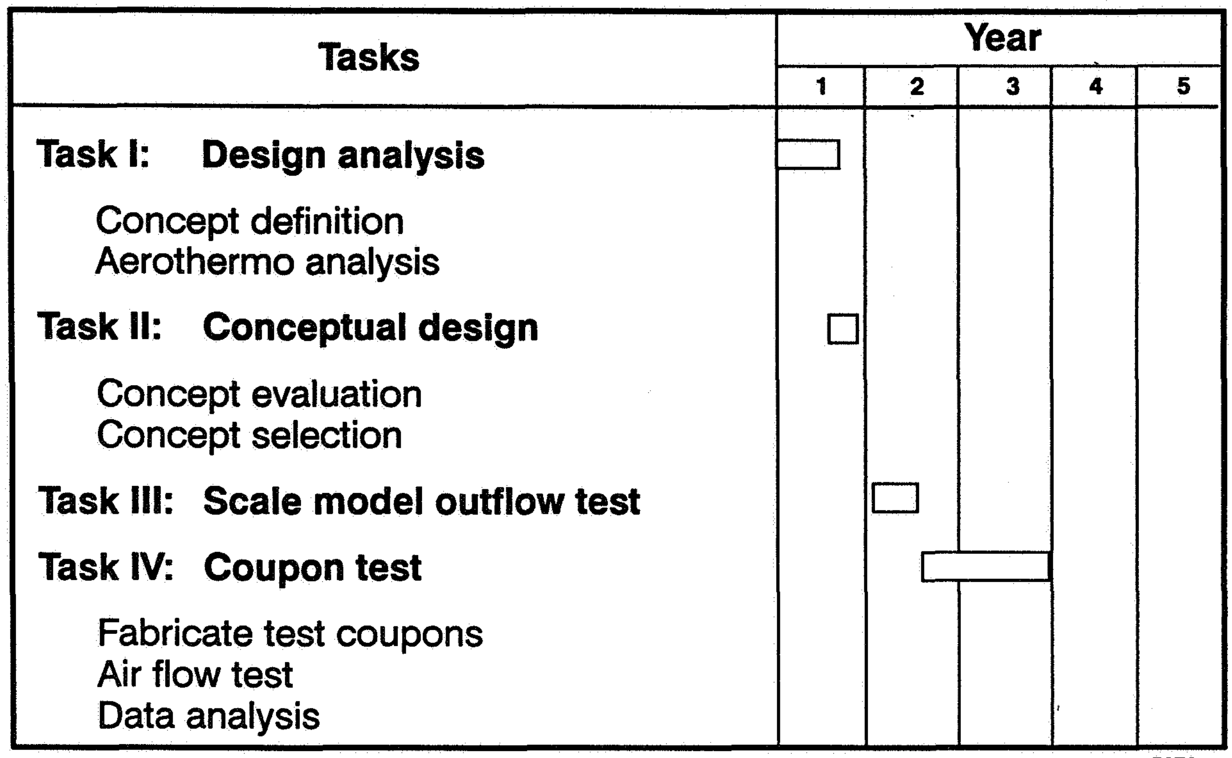
This self–pressurizing propellant tank technology would address 5 operations concerns (Concerns No. 8, 9, 16, 18, and 24). Concerns No. 8, 9, and 18 are addressed by eliminating numerous components and their associated interfaces. Concern No. 16, pertaining to pressurization systems, is completely eliminated since this system removes all operationally inefficient parts of the system. Concern No. 24, contamination issues, is likewise eliminated since pressurant fluid is supplied from the tank itself thus removing the concern of particles passing through hot pressurant gas valves, orifices, and heat exchangers.

9.2 TECHNOLOGY PROGRAM

The recommended approach for developing the technology for this type of system is a four–phase effort. The first phase is an analysis to determine if additional heat is required over that stored in the cryogen itself (which is released as pressure is reduced) and if any additional heat is needed during the time in flight. The second phase is to determine the most promising concepts capable of supplying the necessary heat input into the propellant tanks. One concept to be analyzed is the use of aero–heating to heat propellants sufficiently to supply desired tank pressures. Other concepts which are less sensitive to launch environments must also be considered.

In the third phase, scale model outflow tests are made to verify and anchor the analysis. During the fourth phase, the most promising concepts are selected and small scale test articles are fabricated to verify predicted performance. This would be done by fabricating coupon specimens and subjecting these specimens to flow and thermal tests in the appropriate environments. The data base developed from this testing will allow vehicle designers to evaluate the aero–heating concept and perform trade studies to determine if this concept will be superior to existing methods.

This initial technology task will require approximately 3 years, and the overall schedule is shown in Figure 9–1. The maturity of this technology is estimated to be Level 3.



5872-11

Figure 9-1. Flash Boiling Tank Pressurization Technology Program

10.0 LOW NPSH PUMP TECHNOLOGY

An operationally efficient propulsion system that eliminates engine supplied tank pressurization systems will reduce required checkout and maintenance and increase vehicle reliability and operability. However, eliminating tank pressurization will reduce inlet pressure to engine turbopumps. Therefore, technology that will allow turbopump designs to operate at low inlet pressures, or low net positive suction head (NPSH) levels will be needed.

10.1 OPERATIONS CONCERNS ADDRESSED

When this technology is mature, it will address 4 operations concerns (Concerns No. 13, 16, 19, and 21). Concern No. 13, high maintenance turbopump, is addressed by increasing the turbopumps suction performance thus reducing wear and damage to impellers and bearings. Concern No. 16, pressurization systems, is the driving issue in the development of this technology. Helium spin start, Concern No. 19, is potentially addressed since tank head starts may become feasible with higher pumping efficiencies at lower pressures. Finally, engine preconditioning, Concern No. 21, will be improved since propellant quality requirements at engine start can be reduced with the use of low NPSH pumps.

10.2 TECHNOLOGY PROGRAM

The only near term solution to providing low NPSH capability to the engine is the addition of a boost pump which would increase engine inlet pressure sufficiently to allow operation of the main pumps at nominal levels. Several approaches are suggested. The jet pump, located upstream of the main turbopump, has an advantage of no moving parts. It operates by mixing high velocity fluid with the fluid being pumped. The high velocity fluid is provided by accelerating a small portion of the high pressure main pump discharge flow as the primary flow in the jet pump. This technology is used in many commercial applications; however, at the design and operating conditions in question for a rocket, work still needs to be performed. A boost pump specifically designed for low NPSH of one to two psi level is another approach. This concept is in use today on the Space Shuttle Main Engine (SSME), although not to the extent proposed here. Other approaches include locating the turbopump inlet at the tank, or tank feed manifold, or in the tank sump leaving acceleration head as NPSH. These approaches may require slow start techniques to control fluid quality during the start transient.

The technology development would be largely experimental since most analytical techniques at these levels are not well anchored. The technique would be the same for all pumps discussed. A test unit will be hydrodynamically designed, fabricated, and water flow tested. The data from these tests would be used to optimize the design of the pump further. The optimized pump would be subsequently fabricated and water flow tested. If performance is satisfactory, cryogenic fluid testing would be performed to validate the water flow tests. If performance is not sufficient, additional iteration on the above approach would be performed.

This technology task will require approximately 3 years, and the overall schedule is presented in Figure 10–1. Note that the turbopump technology portion will require more time since the lead time on impeller test articles is longer than that for the comparable jet pump. The maturity of this technology is estimated to be Level 3 to 4.

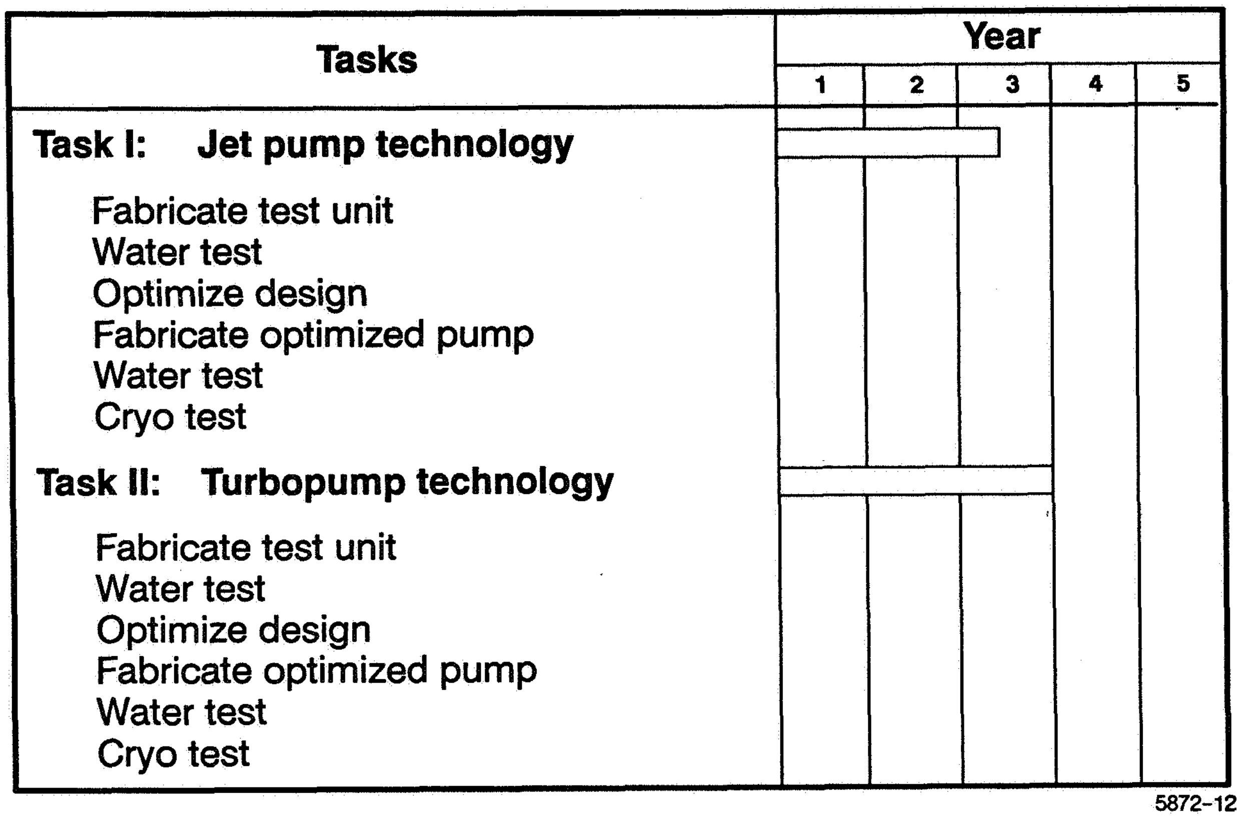


Figure 10–1. Low NPSH Pump Technology Program

11.0 LARGE FLOW RANGE PUMP TECHNOLOGY

The use of a fully integrated propulsion system to achieve operational efficiency is described in OEPSS Data Book: Volume IV – Design Concepts. Such a system minimizes hardware and increases reliability by utilizing a minimum number of turbopumps manifolded together to supply engine thrust chambers. In this system, if a turbopump fails, the remaining pumps would have sufficient operating (flow) margin to power up to maintain propellant supply to the thrust chambers. Another benefit of this system would be its ability to throttle to extremely low levels by shutting down pumps to reduce propellant flow to the chambers. For such a system the development of large flow range pumps would minimize the number of pumps in the system.

11.1 OPERATIONS CONCERNS ADDRESSED

The availability of large flow range pumps allows development of systems which could potentially address 4 operations concerns (Concerns No. 8, 13, 19, and 21). The number of turbopumps required is reduced with an integrated system, thus addressing the parts count issue expressed in Concern No. 8. Concern No. 13 is addressed by reducing the maintenance on turbopumps by reducing the number required. The integrated system has also been determined to have improved start characteristics, thus eliminating the need for a helium assisted spin start and thereby eliminating Concern No. 19. Concern No. 21 is addressed by the simplification of the preconditioning procedures brought about by the integrated system. Propellant bleeds could be eliminated with the use of such a system since turbopumps could be more easily packaged to allow natural percolation during chill.

11.2 TECHNOLOGY PROGRAM

The approach to this technology development is similar to that for the low NPSH pumps, using experimental data to anchor analytical design techniques. The effort would be initiated using existing water flow test models to gather data on design parameters that will increase the pump flow range. Analytical techniques will be anchored by this data to produce an optimized configuration. This large flow range configuration will be fabricated and water flow tested. To assure validity of the water flow test, the pump would then be tested in cryogenic working fluid. To improve the desired results, another iteration on the design and test cycle would be performed.

This technology task will require approximately 3 years, and the overall program schedule is shown in Figure 11–1. The schedule shown is for a single design iteration following test of an initial test unit. The maturity of this technology is estimated to be Level 3 to 4.

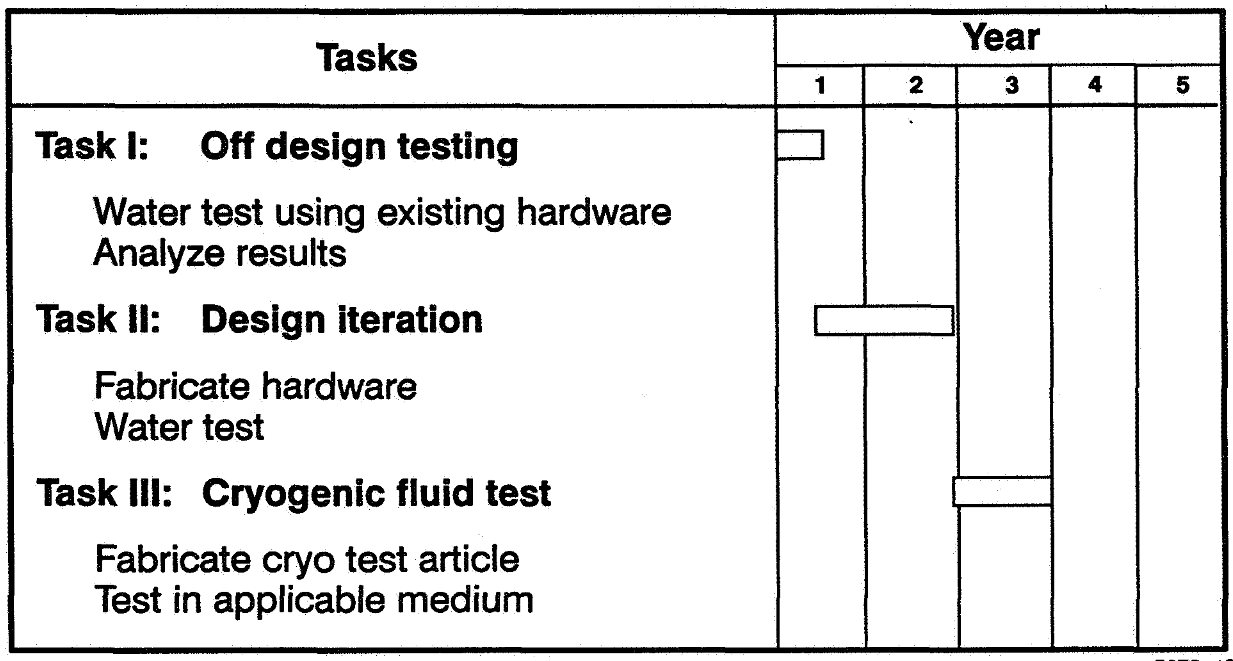


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Figure 11-1. Large Flow Range Pump Technology Program

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16. Abstract

This study was initiated to identify operations problems and cost drivers for current propulsion systems and to identify technology and design approaches to increase the operational efficiency and reduce operations costs for future propulsion systems. To provide readily usable data for the ALS program, the results of the OEPSS study have been organized into a series of OEPSS Data Books as follows: Volume I, Generic Ground Operations Data; Volume II, Ground Operations Problems; Volume III, Operations Technology; Volume IV, OEPSS Design Concepts; and Volume V, OEPSS Final Review Briefing, which summarizes the activities and results of the study. This volume describes operations technologies that will enhance operational efficiency of propulsion systems. A total of 15 operations technologies have been identified that will eliminate or mitigate the operations problems described in Volume II. A recommended development plan is presented for eight promising technologies that will simplify the propulsion system and reduce operational requirements.

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